REPORT DOCUMENTATION PAGE

AFRL-SR-AR-TR-05-

0386

1. REPORT DATE (DD-MM-YYYY)	2. REPORT TYPE	3. DATES COVERED (From - To)
	Final	12/15/2000 - 06/30/2005

4. TITLE AND SUBTITLE
Studies of heavily strained and strain-compensated type-I GaSb based heterostructures for development of high efficiency coherent sources operating in the range of 2.3 -3.5 microns.

5a. CONTRACT NUMBER

5b. GRANT NUMBER
F496200110108

5c. PROGRAM ELEMENT NUMBER

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

6. AUTHOR(S)
Gregory Belenky

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
State University of New York at Stony Brook

NE

8. PERFORMING ORGANIZATION REPORT

20050901 064

9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)

10. SPONSOR/MONITOR'S ACRONYM(S)

11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION / AVAILABILITY STATEMENT
Distribution Statement A: unlimited

13. SUPPLEMENTARY NOTES

14. ABSTRACT

New class of high power continuous wave room temperature operated GaSb-based mid-infrared lasers and laser arrays was developed. World record devices were designed and fabricated.

- 1W CW and 5W pulsed single laser operation was achieved in 2.3-2.5 micron range.
- 500mW continuous wave (2.5W in pulse) and 160mW continuous wave (2W in pulse) was reported for 2.7 and 2.8 micron devices, respectively.
- Linear laser arrays operating at 2.35 microns output 10W in continuous wave and 18.5W in quasi-continuous wave regimes.
- It was shown that there is no fundamental limitation to increase output power level of 2-3 micron GaSb-based lasers since the role of Auger recombination is not decisive.

The technology of new high power mid-infrared lasers was transferred to Sarnoff Corporation and corresponding devices are now commercially available.

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE			19b. TELEPHONE NUMBER (include area code)

Project results

New class of high power continuous wave room temperature operated GaSb-based 2 – 3 μm lasers and laser arrays was developed and transferred to Sarnoff Corporation. High power 2 – 3 μm lasers are now commercially available in US*.

World record 2.3 – 2.5 μm lasers and laser arrays with advanced design were fabricated.

- 1W CW and 5W pulsed single laser operation was achieved at 2.5 micron range.
- Linear laser arrays operating at 2.35 microns output 10W in continuous wave and 18.5W in quasi-continuous wave regimes.

High power room temperature continuous wave operated lasers with wavelengths above 2.5 μm were designed and fabricated for the first time.

- 500mW continuous wave (2.5W in pulse) and 160mW continuous wave (2W in pulse) was reported for 2.7 and 2.8 micron devices, respectively.

Detailed experimental studies and theoretical analysis have shown that there is no fundamental limitation to increase output power level of 2-3 micron GaSb-based lasers and the role of Auger recombination is not decisive. Vital role of quantum well compressive strain in determining laser performance parameters was demonstrated.

* http://www.sarnoff.com/products_services/optoelectronics/mid_ir_laser_ds.pdf

1. Introduction.

Laser sources operating in spectral region 2 - 3 μm are in demand for ultra-sensitive laser spectroscopy, medical diagnostics, home security, industrial process monitoring, infrared countermeasures, optical wireless communications, etc. Currently, solid state lasers and optical parametric oscillators and amplifiers are used as coherent light sources in this spectral region. Solid state and parametric sources are being optically pumped by near infrared diode lasers. This intermediate energy transfer step from near infrared pumping diode to mid infrared emitting device reduces power-conversion system efficiency. Availability of the highly efficient semiconductor diode lasers operating in 2 - 3 μm spectral region will significantly improve the performance of the many existing systems and enable new applications.

In the framework of this project we have achieved major breakthrough in the development of the GaSb-based technology of high power room temperature operated mid-IR type-I QW diode lasers. World record power levels were obtained as a result of detailed experimental studies of the physical mechanisms underlying laser performance peculiarities. Future directions in device performance optimization and enhancement of the wavelength for high power room temperature operation were identified.

2. Compressively strained quantum wells for 2.3-2.5 micron wavelength range.

GaSb-based type-I QW mid-infrared diode laser heterostructure includes several InGaAsSb quantum wells in AlGaAsSb separate optical confinement waveguide layer. Cladding layers are also made of AlGaAsSb compound but with higher Al content. Both InGaAsSb and AlGaAsSb quaternary alloys were predicted to have large miscibility gaps **[1]**. Fortunately, condition of lattice matching of AlGaAsSb to GaSb substrate requires low As content and AlGaAsSb compounds used for laser fabrications are thermodynamically stable. Situation with InGaAsSb is more complicated. For type-I InGaAsSb/AlGaAsSb QWs to operate at wavelength longer than 2 μm and to avoid miscibility gap, the InGaAsSb has to be compressively strained. First works extending operation of the GaSb-based diode lasers in 2.3 – 2.6 μm region used quasi-ternary InGaAsSb compounds with As content below 2% **[2]**. Those devices had wide (> 20nm) QWs to minimize quantum confinement effect. Maximum wavelength was limited because QW strain relaxed for In content above 40%. *To avoid this limitation we have designed and fabricated the lasers based on true quaternary InGaAsSb material.* In these devices the As content was increased up to ~14% for 41% In. The QW material composition was still kept away from miscibility gap but compressive strain was reduced to safe level (~1.6%).

3. Performance of high power 2.3-2.5 micron lasers and laser arrays.

Figure 1a shows room temperature CW light-current characteristics of 1mm-long anti-/high-reflection coated 2.3 and 2.5 μm diode lasers with two $In_{0.41}Ga_{0.59}As_{0.14}Sb_{0.86}$ QWs in active region. Maximum CW power level for 1-mm-long 100-μm-wide p-side down mounted devices was near 700mW at both 2.3 and 2.5 μm. The laser wavelength was adjusted by changing the QW width (~11.5nm for 2.3 μm and ~ 14.5nm for 2.5 μm lasers). The design of the laser heterostructure was: 2 μm wide $Al_{0.9}Ga_{0.1}As_{0.075}Sb_{0.925}$ p and n-cladding layers, ~ 800nm wide $Al_{0.25}Ga_{0.75}As_{0.02}Sb_{0.98}$ separate optical confinement layer. Two QWs were located in the middle of the separate optical confinement layer separated by ~ 200 nm.

Figure 1b shows the modal optical gain spectra measured at several currents below threshold for 2.3 and 2.5 μm lasers. The differential gain with respect to current of 80-90 cm^{-1}/A was measured for both devices. It is instructive to compare the differential gains of 1.5μm InP-based and 2.3 – 2.5 μm GaSb-based high power lasers. The differential gain of 1.5 μm lasers with QW optical confinement and injection efficiency similar to 2.3-2.5 μm devices was measured to be ~40-50 cm^{-1}/A **[3]**. The twice difference in differential gains allows contemplating that threshold carrier concentration is rather low in GaSb-based mid-IR lasers. Low threshold carrier concentration mitigates the role of Auger recombination, which for a long time was thought to have devastating effect on long wavelength laser room temperature operation.

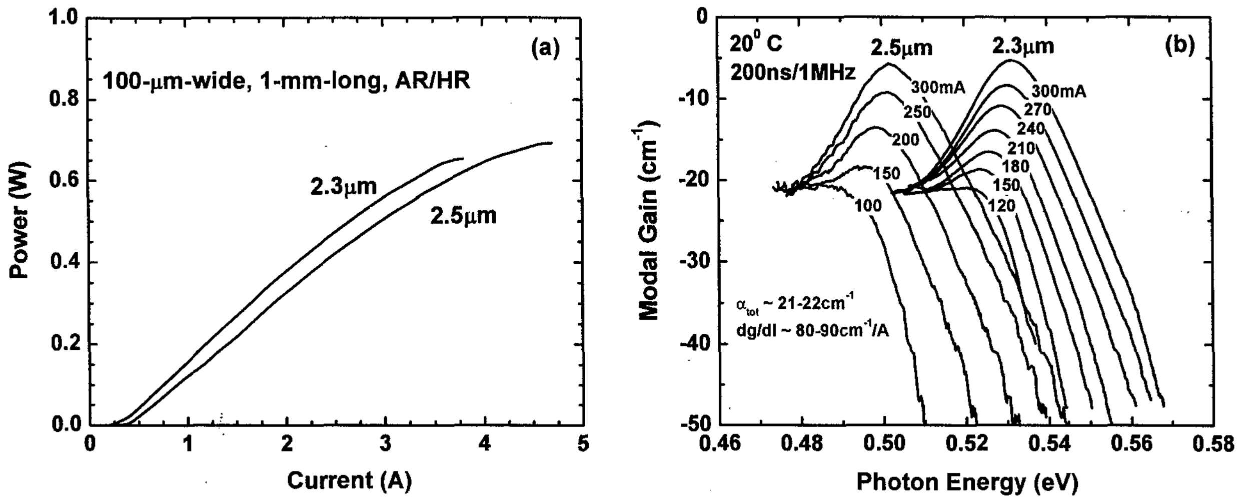

Figure 1. Continuous wave light-current characteristics (a) and current dependences of modal optical gain (b) of 2.3 and 2.5 μm lasers at room temperature.

We have performed studies of the prevailing recombination mechanisms in GaSb-based devices. Figure 2 shows the current dependences of the spontaneous emission SE(I) measured from the laser side for the 2.3 μm lasers at 200, 260 and 320K.

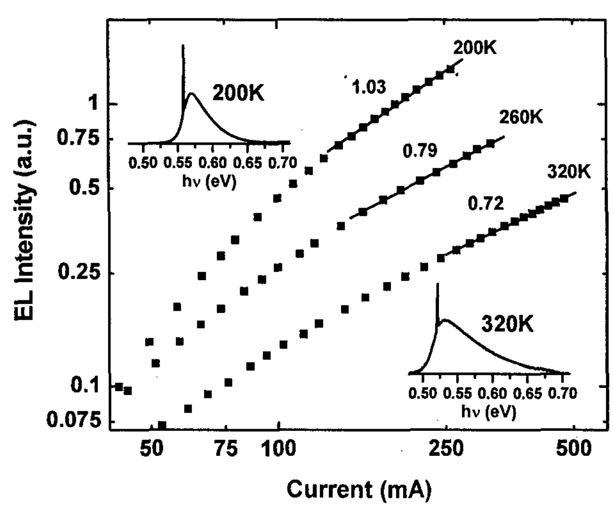

Figure 2. Current dependence of the integrated spontaneous emission in 2.3 μm laser at 200, 260 and 320K. Inserts show spontaneous emission spectra after threshold at 200 and 320K.

Each point on these dependences was obtained by measuring spontaneous emission spectrum followed by numerical integration. The slope of SE(I), plotted in double logarithmic scales, is determined by carrier recombination mechanisms. Integrated spontaneous emission is proportional to n^2, where n is the QW electron concentration. Net current through the laser heterostructure is proportional to the sum of all possible recombination currents, i.e., $I \sim An + Bn^2 + Cn^3$, where An is the non-radiative, monomolecular recombination; Bn^2 is the radiative bimolecular recombination; and Cn^3 is the Auger recombination process. Reduction of the slope with temperature reveals the increasing role of Auger recombination at high temperature. *However, the effect of Auger recombination is not decisive and devices operate at room temperature in CW mode. We speculate that it is high compressive strain that increases the device differential gain in GaSb-based lasers.* After the differential gain increases, the threshold carrier concentration is reduced and so is net Auger rate.

GaSb-based heavily strained type-I QW lasers were used successfully to fabricate room temperature operating high power laser arrays. The 2.3 μm wafer was processed into 1-mm-long, 1-cm-wide laser bars having a 20 % fill-factor. Each single gain-guided element aperture was 100 μm. The facets were coated to reflect 3% and 95% and soldered into a microchannel-cooled Be-O heatsink.

Figure 3 shows the room temperature light-current characteristics of 2.3 μm laser array. *The maximum CW power of 10 W is reached at 70 A.* The spectrum is centered near 2.36 μm with a FWHM of about 20 nm at 30 A CW. In the qCW mode (30 μs, 300 Hz, 0.9 % duty cycle) the array output over 18.5 W peak power at a peak current of 100 A. In the short-pulse, low-duty-cycle mode, the light current characteristics is linear up to nearly 20W of peak power at 100 A of peak current without any cooling. *Successful fabrication of the high power laser arrays demonstrates that GaSb-based laser technology has grown mature enough for wide deployment.*

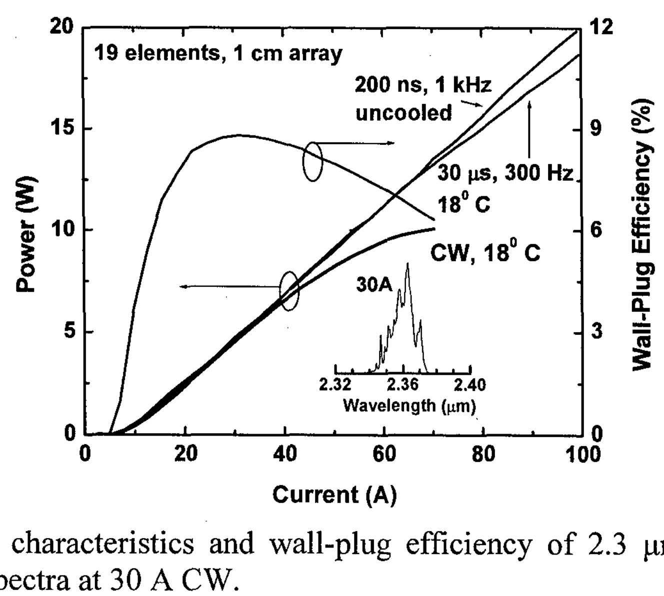

Figure 3. Light-current characteristics and wall-plug efficiency of 2.3 μm linear laser array. Insert shows emission spectra at 30 A CW.

Array power conversion efficiency is below 10%. This means that the heating in the CW regime of operation is substantial – array dissipates more than 100 W in heat at the highest currents. The measured package thermal resistance is about 0.5 K/W leading to active region overheating by more than 50°C. It is high temperature stability of the 2.3 μm laser heterostructure that enables high power CW array operation. The parameters T_0 and T_1 characterizing temperature dependence of the laser threshold current and slope efficiency are 95 and 180K, respectively. For comparison, parameter T_0 in InP-based 1.5 μm lasers is rarely above 60K due to pour electron confinement barriers. High temperature stability of the mid-infrared GaSb-based type-I QW lasers stems from large carrier confinement barriers between QW and waveguide and between waveguide and claddings.

Important design feature of our mid-infrared lasers is broadened waveguide reducing overlap of the optical mode with heavily doped cladding regions. This approach is especially effective in mid-IR spectral range where free carrier absorption is high. Low internal loss obtained with broadened waveguide design allows using longer cavity lengths for more efficient heat removal. Increase of the cavity length of 2.5 μm lasers to 2 mm led to 1W CW maximum power level (see Figure 6).

4. Linewidth enhancement factor in 2-2.5 micron GaSb-based lasers.

Spectra of the linewidth enhancement factor of high-power 2, 2.3 and 2.5 μm InAlGaAsSb/GaSb type-I QW lasers were measured using Hakki–Paoli technique. The corresponding laser designs were as described above but the two QW compressive strains and thicknesses. Namely, for 2 μm and 2.3 μm lasers - 22nm with 0.9 and 1.1%, respectively, and for 2.5 μm lasers – 14.5nm and 1.6% (same as for devices in Figure 1).

Spectra of the α-factor were obtained from the current dependence of the amplified spontaneous emission (ASE) measured from the laser front facet. A spatial filtering technique was used to filter out ASE of the on-axis mode of 100-μm-stripe width multimode lasers. ASE emission was measured in pulses ~100 ns, 1 MHz in order to minimize effect of Joule heating on laser characteristics.

Lasers emitting at 2 and 2.3 μm have α equal to 3.3 and 3.8, respectively, while 2.5 μm devices have smaller value of 2.5 (Figure 4).

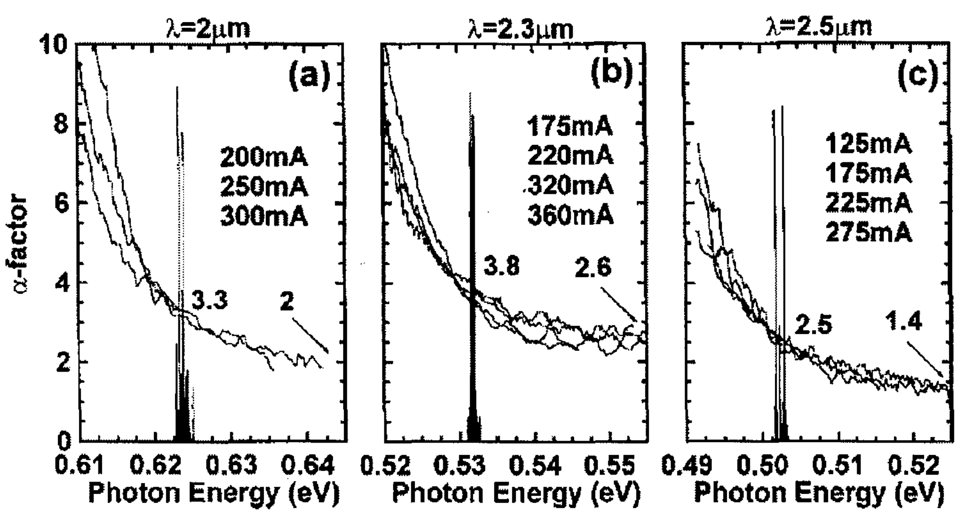

Figure 4. Linewidth enhancement factor spectra for 2 μm, 2.3 μm, and 2.5 μm lasers at 20 °C for different currents below threshold. Spectra of the laser emission just after threshold are shown in each laser for reference.

The lower value of α-factor for 2.5 μm, comparing to 2 and 2.3 μm devices, can be attributed to the higher compressive strain incorporated in the QW region (1.5%–1.6% versus about 1%) and smaller QW width (~14.5 nm versus 22 nm) of 2.5 μm laser structure. Compressive strain and quantum confinement reduce the heavy hole effective mass. Decrease of the heavy hole effective mass moves quasi-Fermi levels closer to the electron states coupled to the laser mode, thereby increasing differential gain at the lasing wavelength.

5. High brightness tapered lasers.

Tapered lasers emitting at 2.4μm are fabricated and tested. Devices with 1mm-long ridge waveguide and 1mm-long 6 degree tapered waveguide give more than 80mW with the main power in diffraction limited central lobe however significant emission of the higher order modes is present in far field (Figure 5).

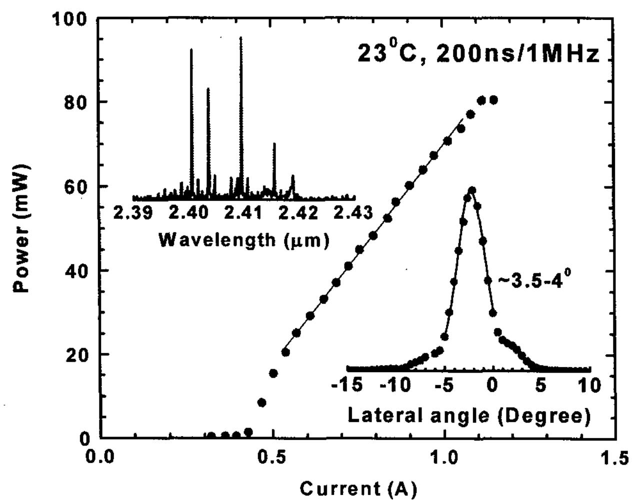

Figure 5. Light-current characteristics of 2.4-μm tapered laser with 1-mm-long ridge and 1-mm-long tapered sections. Inserts show emission spectrum and uncorrected lateral far field.

6. Increase of the device wavelength above 2.5 microns.

In order to extend the type-I MQW GaSb-based laser wavelength further more In and As is required in QW. *We have designed and fabricated 2.7 and 2.8μm lasers emitting 500mW and 160mW, correspondingly, in CW regime at room temperature (Figure 6a). In pulsed mode the power level was well above 2W.* Decrease of the output power with wavelength is in large associated with decrease of the hole confinement for As-rich QWs.

7. Role of hole confinement and Auger recombination.

Temperature dependence of the laser efficiency was measured from 200K to 320K (Figure 6b) for 2.5, 2.7 and 2.8μm devices. The 2.8 μm devices have stronger temperature sensitivity. It is also reflected in measured T_0 values, for 2.7 and 2.8 μm lasers T_0 are 71 and 59K, correspondingly, while for 2.5 μm lasers T_0 is 95K. The composition of the QWs for 2.7 and 2.8 μm devices was $In_{0.5}Ga_{0.5}As_{0.19}Sb_{0.81}$ and $In_{0.5}Ga_{0.5}As_{0.26}Sb_{0.74}$, respectively. More As in 2.8 μm QWs leads to about 70meV reduction of the valence band offset as compared to 2.5 μm lasers **[4]**. No direct heterobarrier hole leakage was observed in these structures **[5]**. Hole escape from the QWs into the $Al_{0.25}Ga_{0.75}As_{0.02}Sb_{0.98}$ waveguide layers and their subsequent nonradiative recombination reduces laser injection efficiency.

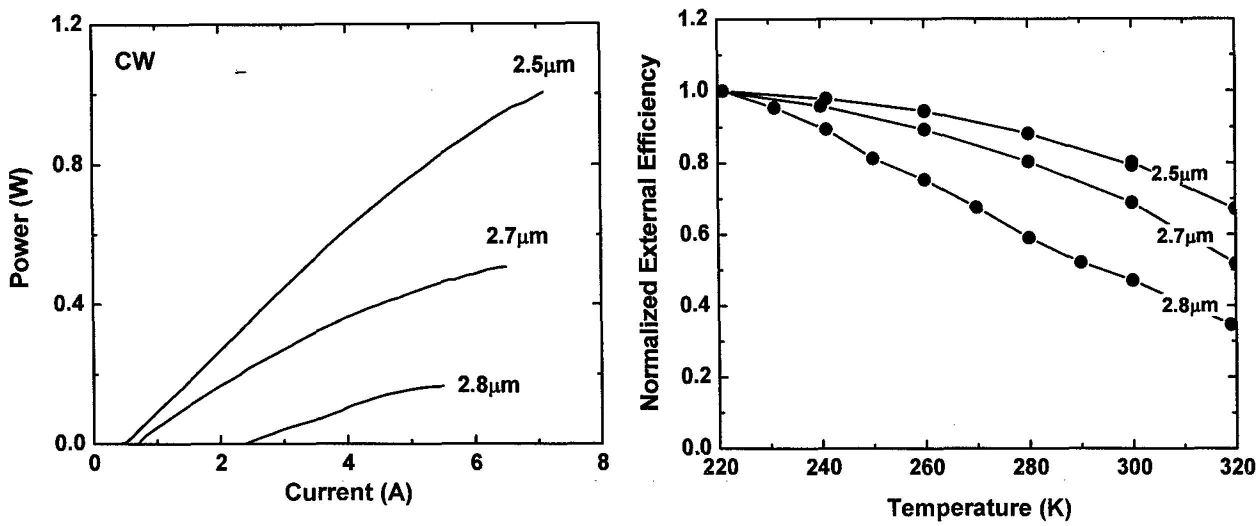

Figure 6. Temperature dependence of the 2.5, 2.7 and 2.8 μm laser efficiencies normalized to their values at 220K

8. Summary and further outlook.

We have achieved significant advances in development of the mid-infrared room temperature CW operated diode lasers with wavelength longer than 2 μm. We have demonstrated 1 W CW at 2.5 μm, 500 mW and 160 mW CW at 2.7 and 2.8 μm, respectively. Linear laser array operating at 2.3μm was designed and fabricated for the first time. Array output 10W CW power from 1cm length. Corresponding device technology was transferred to Sarnoff Corporation.

Our experimental results show that there is no fundamental limitation to extend CW RT operating wavelength of these devices to over 3 μm spectral region. It is carrier leakage and material quality issues that limit device performance at wavelength longer than 2.5 μm. The role of Auger recombination is not decisive in type-I MQW GaSb-based lasers. We speculate that it is high differential gain and, as a result, low threshold carrier concentration that can account for muted effect of Auger on type-I GaSb-based laser performance.

The extension of type-I device operating wavelength above 3 μm can be realized utilizing dilute-nitride GaSb-based material for QW material. It was recently shown that incorporating nitrogen into various III-V semiconductors decreases the material bandgap at the rate of more than 100meV per atomic percent **[6,7]**. Besides increasing the laser wavelength, the introduction of a small fraction (1-2 atomic percent) of nitrogen into InGaAsSb QW can reduce the QW compressive strain and even suppress the intensity of Auger recombination **[7]**.

The position of the valence band edge of a dilute-nitride (N<2%) InGaAs(N)Sb QW is nominally independent of the nitrogen content, and the bandgap reduction comes entirely from a large bowing of the conduction band edge. Therefore, the hole confinement barrier is almost unchanged as the QW bandgap decreases. In contrast, for N-free InGaAsSb QWs the bandgap decrease is accompanied by a valence-band offset reduction. Our estimation shows that adding just 1% of nitrogen into $In_{0.5}Ga_{0.5}As_{0.19}Sb_{0.81}$ 2.7μm laser QW should increase the laser wavelength up to 3.5μm. Laser emission can reach over 4μm if the nitrogen content is increased up to 2%. We are currently optimizing the dilute-nitride GaSb-based material growth conditions.

References

1. K. Onabe, "Unstable regions in III-V quaternary solid solutions composition plane calculated with strictly regular solution approximation, Jap. J. Appl. Phys. **21**, L323 (1982).

2. D.Z. Garbuzov, H. Lee, V. Khalfin, R. Martinelli, J.C. Connolly, G.L. Belenky "2.3-2.7μm room temperature CW operation of InGaAsSb/A1GaAsSb broad waveguide SCH-QW diode lasers" IEEE Photon. Tech. Lett. **11** (1999) 794

3. G. Belenky, L. Shterengas, C.W. Trussell, C.L. Reynolds, Jr., M.S. Hybertsen, R. Menna, "Trends in semiconductor laser design: Balance between leakage, gain and loss in InGaAsP/InP MQW structures" Advanced Research Workshop on "Future Trends in Microelectronics: The Nano Millennium" (2002), Wiley ISBN: 0-471-21247-4, p. 231.

4. M.P.C.M. Krijn "Heterojunction band offsets and effective masses in III-V quaternary alloys", Semicond. Sci. Technol. **6**, 27 (1991).

5. D.V. Donetsky, G.L. Belenky, D.Z. Garbuzov, H. Lee, R.U. Martinelli, G. Taylor, S. Luryi, J.C. Connolly "Direct measurements of heterobarrier leakage current and modal gain in 2.3μm double QW p-substrate InGaAsSb/AlGaAsSb broad area lasers", IEE Electron. Lett. **35**, 298 (1999)

6. M. Kondow, T. Kitatani, M.C. Larson, K. Nakahara, K. Uomi, H. Inoue "Gas-source MBE of GaInNAs for long-wavelength laser diodes", J. Crystal Growth, **188** (1998) 255; W. Ha, V. Gambin, S. Bank, M. Wistey, H. Yuen, S. Kim, J.S. Harris "Long-wavelength GaInNAs(Sb) lasers on GaAs", IEEE J. Quant. Electron. **38** (2002) 1260; J.-C Harman, A. Caliman, E.V.K. Rao, L. Largeau, J. Ramos, R. Teissier, L. Travers, G. Ungaro, B. Theys, I.F.L. Dias "GaNAsSb: how does it compare with other dilute III-V-nitride alloys", Semicond. Sci. Technol. **17** (2002) 778

7. B.N. Murdin, M. Kamal-Saadi, A. Lindsay, E.P. O'Reilly, A.R. Adams, G.J. Nott, J.G. Crowder, C.R. Pigeon, I.V. Bradley, J.-P.R. Wells, T. Burke, A.D. Johnson, T. Ashley "Auger recombination in long-wavelength infrared InN_xSb_{1-x} alloys", Appl. Phys. Lett. **78** (2001) 1568

Supported Personnel

G.L. Belenky	Professor
L.E. Vorobiev	Professor (Consultant)
A. Gourevitch	Ph.D. Student
L. Shterengas	Ph.D. Student/Postdoctoral Associate
D. Westerfeld	Ph.D. Student

This work was accomplished in close collaboration with the Laser Group of Sarnoff Corporation.
Novel laser technology was transferred to Sarnoff Corporation and corresponding lasers are now commercially available in US.

Dissertations

The work performed under the umbrella of this project constitutes significant part of the PhD dissertation of Dr. Leon Shterengas "Design and characterization of InP and GaSb-based semiconductor lasers", SUNY at Stony Brook 2003.

Publications

Journal papers

1. P.J. McCann, P. Kamat, Y. Li, A. Sow, H.Z. Wu, G. Belenky, L. Shterengas, J.G. Kim, R. Martinelli, "Optical pumping of IV-VI semiconductor multiple quantum well materials using a GaSb-based laser with emission at lambda=2.5 μm", J. Appl. Phys. 97 (2005) 053103;
2. L. Shterengas, G.L. Belenky, A. Gourevitch, D. Donetsky, J.G. Kim, R.U. Martinelli, D. Westerfeld, "High power 2.3-μm GaSb-based linear laser array", IEEE Photon. Tech. Lett. 16 (2004) 2218;
3. G.L. Belenky, J.G. Kim, L. Shterengas, A. Gourevitch, R.U. Martinelli, "High power 2.3-μm laser arrays emitting 10 W CW at room temperature", IEE Electron. Lett 40 (2004) 737;
4. L. Shterengas, G.L. Belenky, J.G. Kim, R.U. Martinelli, "Design of high-power room-temperature continuous-wave GaSb-based type-I quantum-well lasers with lambda >2.5μm", Semicond. Sci. Tech. 19 (2004) 655;
5. G.L. Belenky, L. Shterengas, J.G. Kim, R.U. Martinelli, L.E. Vorobiev, "Design and continuous-wave room temperature performance of GaInAsSb/AlGaAsSb type-I electrically pumped lasers" Advanced Research Workshop on "Future Trends in Microelectronics: the Nano, the Giga, and the Ultra" (2004), Wiley ISBN: 0-471-48405-9, p. 349;
6. J.G. Kim, L. Shterengas, R.U. Martinelli, G.L. Belenky, "High-Power Room-Temperature Continuous Wave Operation of 2.7- and 2.8 μm In(Al)GaAsSb/GaSb Diode Lasers" Appl. Phys. Lett. 83 (2003) 1926;
7. J.G. Kim, L. Shterengas, R.U. Martinelli, G.L. Belenky, D.Z. Garbuzov, W.K. Chan, "Room-Temperature 2.5 μm InGaAsSb/AlGaAsSb Diode Lasers Emitting 1W Continuous-Wave", Appl. Phys. Lett. 81 (2002) 3146;
8. L. Shterengas, G.L. Belenky, J.G. Kim, R.U. Martinelli, "Measurements of α-factor in 2-2.5 μm type-I In(Al)GaAsSb/GaSb high power diode lasers", Appl. Phys. Lett. 81 (2002) 4517;

Invited conference presentations

1. GaSb-based lasers for spectra region 2 - 4 μm: challenges and limitations", Photonics West, January 24-29 (2005), San Jose, California, USA, Proc. SPIE Int. Soc. Opt. Eng. 5732 (2005) 169;
2. G.L. Belenky, J.G. Kim, L. Shterengas, R.U. Martinelli, "Mid-IR room temperature operated GaSb-based lasers and laser arrays", 17th Annual Meeting of the IEEE Laser and Electro-Optics Society, November 7—11 (2004), Puerto Rico, Proc. v.2 p.553;
3. G. Belenky, S. Suchalkin, S. Luryi, L. Shterengas, J. Bruno, R. Tober, R.U. Martinelli, J.G. Kim, "2 μm – 5 μm GaSb based emitters for free space communications. Challenges and limitations", SPIE International Symposium "Information Technology and Communication", October 25-28 (2004), Philadelphia, Pennsylvania, USA;
4. G.L. Belenky, L. Shterengas, J.G. Kim, R.U. Martinelli, "Recent performance advances in type I GaSb based lasers", 6th International Conference "Mid-Infrared Optoelectronics Materials and Devices", June 28 - July 02 (2004), Saint-Petersburg, Russia;

5. L. Shterengas, G.L. Belenky, J.G. Kim, R.U. Martinelli, "Design of High-Power Room-Temperature CW GaSb-based Type-I QW Lasers with lambda > 2.5 μm", 205 Electrochemical Society Meeting, May 9-13 (2004), San Antonio, Texas, USA;

6. J.G. Kim, R.U. Martinelli, L. Shterengas, G.L. Belenky, "High-power room-temperature continuous operation of type-I In(Al)GaAsSb/GaSb diode lasers at wavelength greater than 2.5 μm", Photonics West, January 24-29 (2004), San Jose, California, USA, Proc. SPIE Int. Soc. Opt. Eng. 5365 (2004) 240;

7. R.U. Martinelli, J.G. Kim, G.L. Belenky, L. Shterengas, "Design and performance of AlGaAsSb/InGaAsSb/GaSb type-I quantum-well diode lasers", Conference on Lasers and Electro-Optics, June 1-6 (2003) Baltimore, Maryland, USA.

Conference presentations

1. G. Belenky, L. Shterengas, A. Gourevitch, D. Donetsky, J. Kim, R.U. Martinelli, D. Westerfeld, "2.3-μm GaSb-based diode laser linear arrays emitting 10W CW at room temperature", Solid State and Diode Laser Technology Review SSDLTR-04, June 8-10 (2004) Albuquerque, New Mexico, USA, Proc. p-20;

2. L. Shterengas, J.G. Kim, G. Belenky, R. Martinelli, "Progress in type-I In(Al)GaAsSb/GaSb diode lasers with lambda > 2.5 μm", Conference on Lasers and Electro-Optics, June 1-6 (2003) Baltimore, Maryland, USA;

3. G. Belenky, J.G. Kim, L. Shterengas, R.U. Martinelli, D. Garbuzov, "Gain, Loss and α-factor in 2.5 μm In(Al)GaAsSb Type-I QW Lasers with 1W CW Output Power", 18th IEEE International Semiconductor Laser Conference at the Kongresshaus Garmisch-Partenkirchen, 29 September-3 October (2002) Garmisch, Germany;

4. L. Shterengas, A. Gourevitch, J.G. Kim, R. Martinelli, G. Belenky, "Measurements of α-factor in 2-2.5 μm type-I In(Al)GaAsSb/GaSb broadened waveguide lasers" Conference on Lasers and Electro-Optics, May 19-24 (2002), Long Beach, California, USA, Proc. p. 157;